Development Novel Carbon Sorbents for Carbon Dioxide Capture

2011 NETL CO_2 Capture Technology Meeting

August 22-26, 2011 in Pittsburgh, PA.

Profile of SRI International

SRI is one of the world's largest independent R&D organizations

- Founded 1946 as the Stanford Research Institute in conjunction with Stanford University
- Independent, not-for-profit scientific research institute with for-profit spin-offs and subsidiaries
- Creating and delivering innovative science and technology solutions for governments and businesses worldwide.

- Annual combined revenues exceed $500 million:
- 2,100 employees, 700 with advanced degrees
- Headquarters in Menlo Park, CA, offices in Washington, D.C. and throughout the U.S.

Project Overview

- Participants:
  - SRI International, Menlo Park, CA
  - ATMI, Inc., Danbury, CT
  - DOE-National Energy Technology Center
- Period of Performance:
  - 10-1-2008 through 9-30-2011
- Funding:
  - U.S.: Department of Energy: $1.35 million
  - Cost share: $0.45 million
  - Total: $1.8 million

Team

- SRI International
  - Dr. Gopala Krishnan – Associate Director (MRL) and PI
  - Dr. Marc Hornbostel, Senior Materials Scientist
  - Dr. Jianer Bao, Materials Scientist
  - Dr. Angel Sanjurjo – Materials Research Laboratory Director and Project Supervisor.
- ATMI Inc.
  - Sorbent developer, Industry perspective
  - Dr. Joshua B. Sweeney, Director, Business Development
  - Dr. Melissa Petruska, Materials Scientist
  - Dr. Donald Carruthers; Senior Research Scientist
  - Dr. Lawrence H. Dubois, Senior Vice President and Chief Technology Officer.
- DOE-NETL
  - Andrew O'Palko

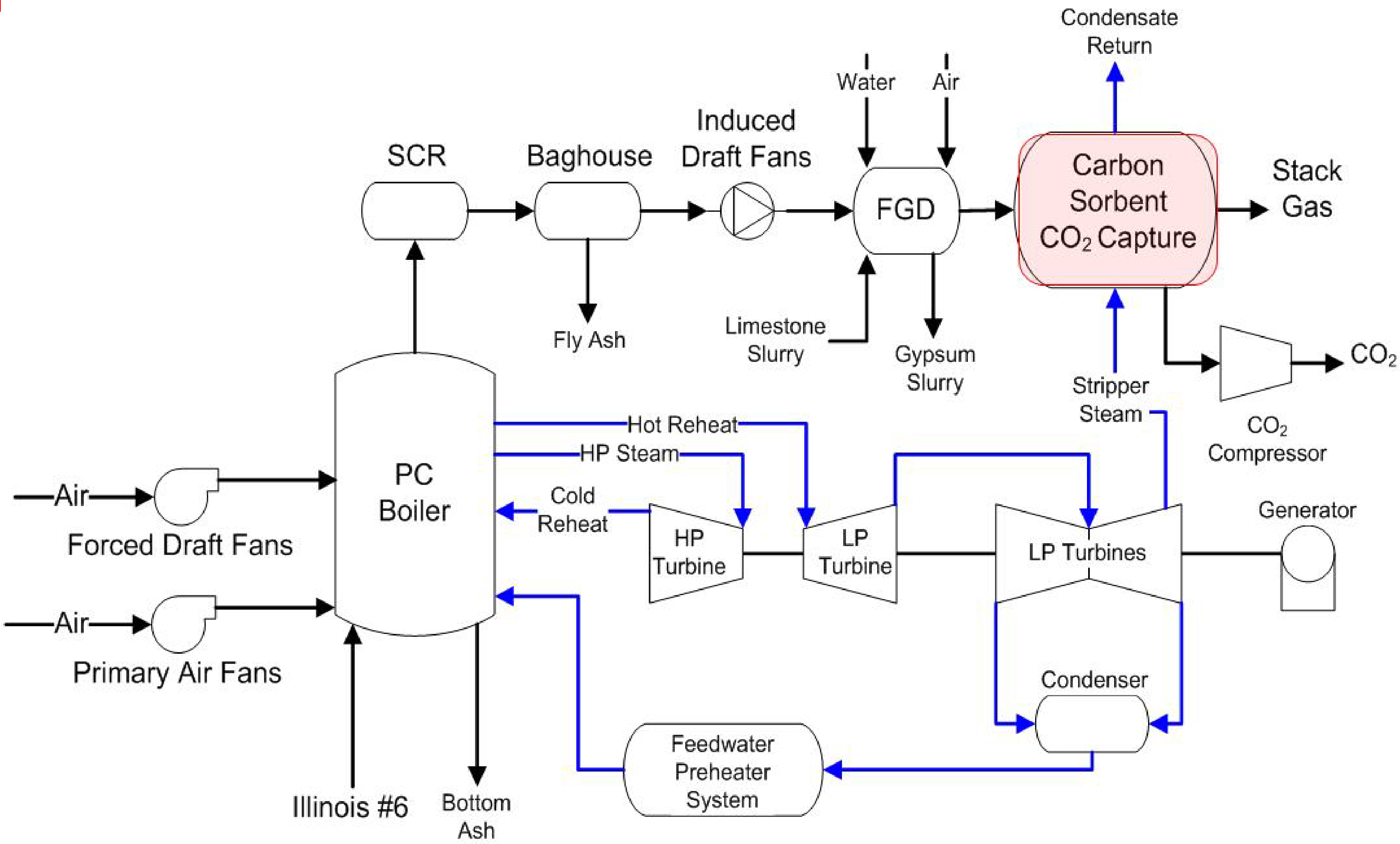
Basic Principles

- Adsorption of CO_2 from flue gas on a selective and high capacity carbon sorbent.
- Ability to achieve rapid adsorption and desorption rates (no solid state diffusion limit).
- Minimize thermal energy requirements
- Ability to desorb as pure CO_2.
- A cascading reactor geometry integrating the adsorber and stripper in a single vertical column
  - Provides a low pressure drop for gas flow and minimize physical handling of the sorbent.

Project Objectives

- Validate the performance of novel carbon sorbents for CO_2 capture on a bench-scale system for post-combustion applications.
- Perform parametric experiments to determine the optimum operating conditions.
- Evaluate the technical and economic viability of the technology.
- Pilot-scale testing in a future phase

Block Flow Diagram



Project Tasks

- Determination of the relevant properties of the sorbent.
  - Surface area, heat of adsorption and desorption, compressive strength and attrition resistance, size and shape of the sorbent particles.
- Improvements to the properties of the sorbent.
  - Structural modification of the pore structure
  - Functionalizing the surface
- Bench-scale parametric testing of the sorbent for adsorption and regeneration:
  - Screening tests
  - Parametric tests
  - Long-term tests
- Process technical and economic analysis.

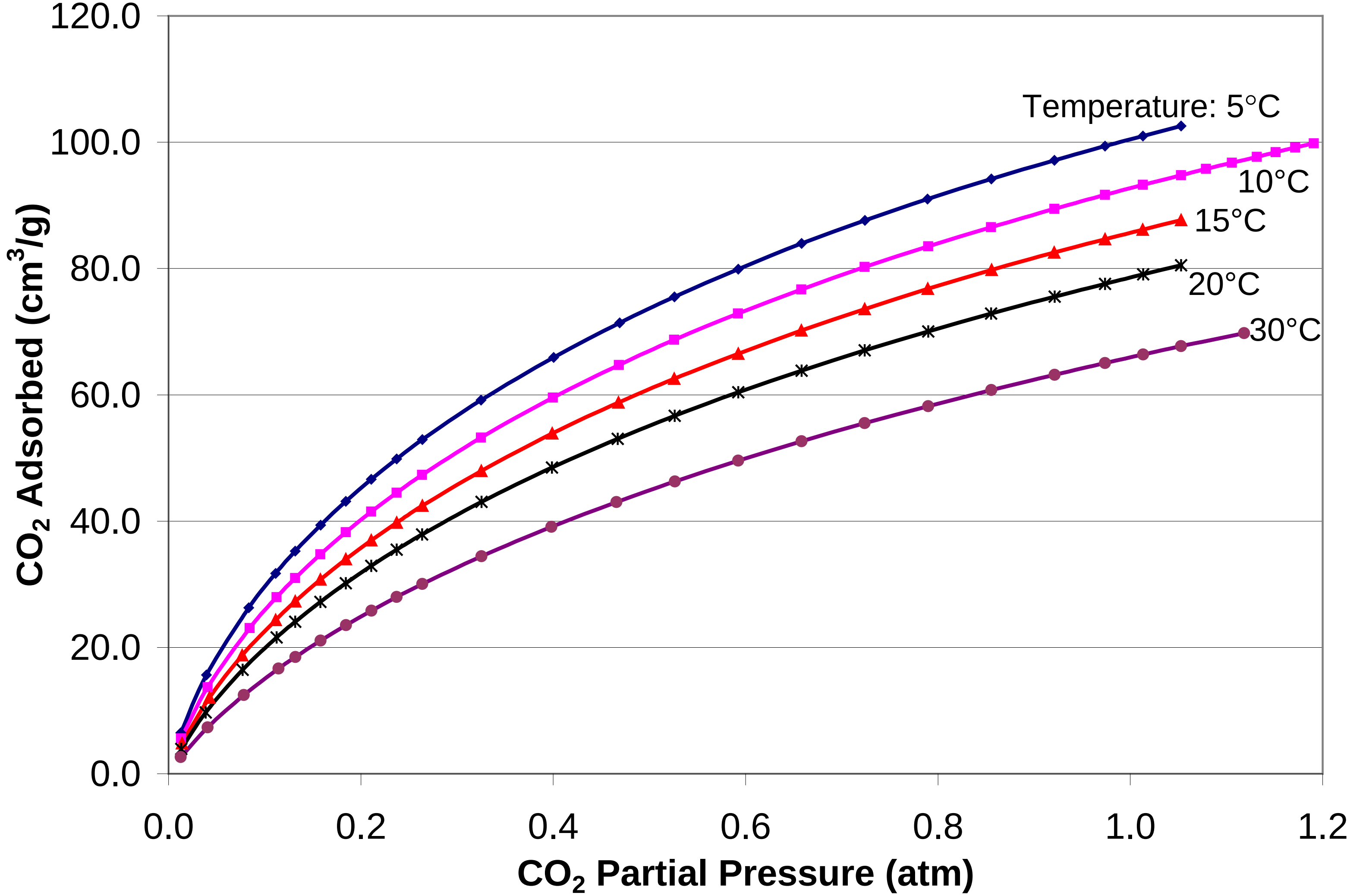
Summary of Previous Reported Results

- Adsorption/desorption isotherms
  - Gives capacity of sorbent as a function of temperature and CO_2 pressure
- Heat of adsorption and desorption
  - Gives cooling requirements during adsorption and heating requirements during regeneration
  - Provides a guide to improving sorbent for CO_2 selectivity
- Compression strength and attrition resistance, particle size and shape
  - Determines suitability for use in moving bed reactors
- Determine the CO_2 capture rate of the current and improved sorbents in a small bench-scale reactor
  - At 20 C using a simulated flue gas containing air and CO_2.
  - Determine the adsorption kinetics and the CO_2 loading
- Rapidly heat to 120 C to desorb the CO_2:
  - Determine the desorption kinetics and the CO_2 desorbed.
- Limited number adsorption-regeneration cycles with selected sorbents

Merits of the Sorbent – Chemical Properties

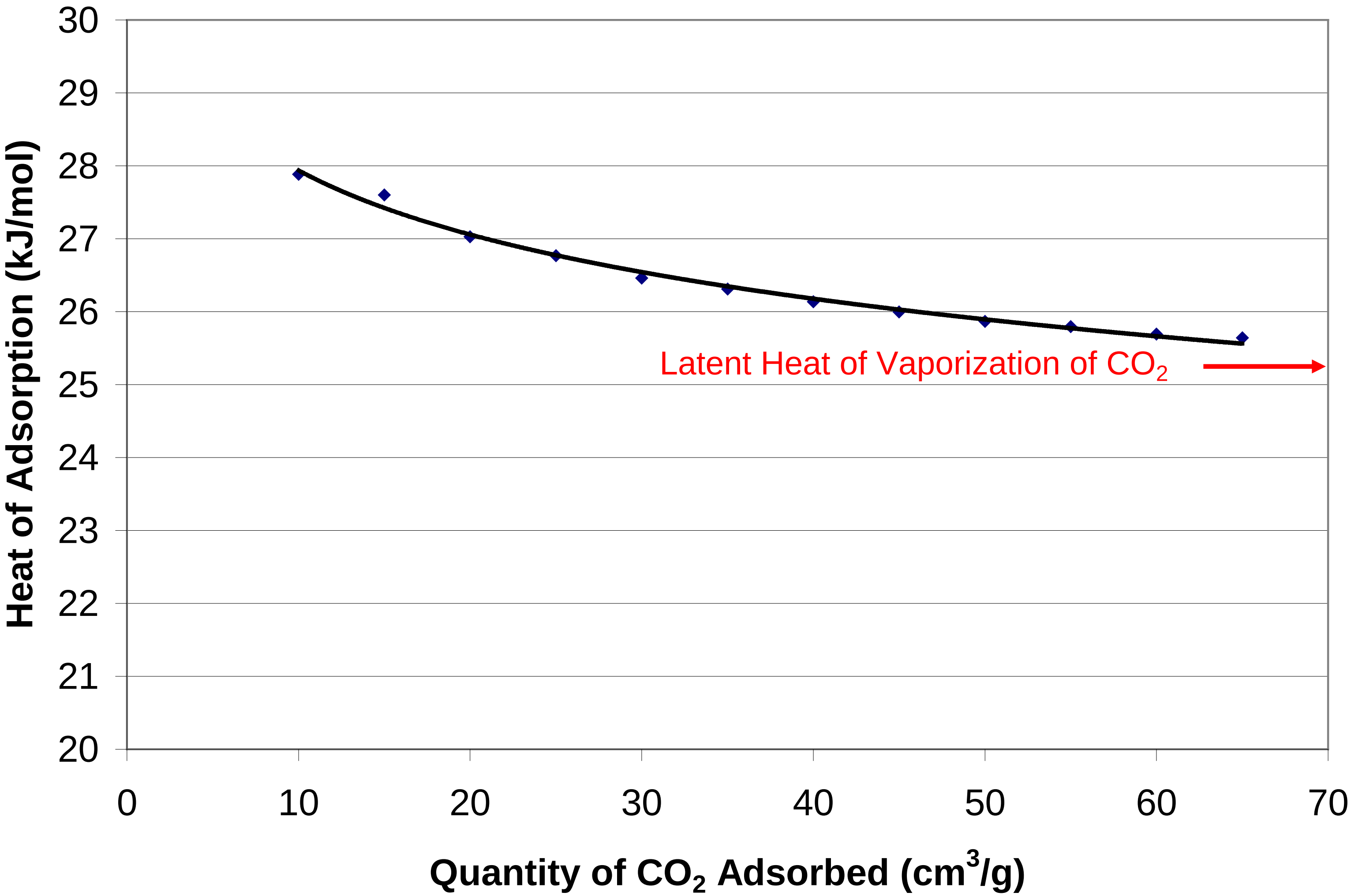
- High CO_2 capacity:
  - The sorbent has a high capacity for CO_2 adsorption (20 wt% at 1 atm CO_2) and good selectivity for CO_2 over other flue gas components.
- Rapid adsorption and desorption rates:
  - The adsorption of CO_2 occurs on the micropores of the sorbent with very low activation energy (<5 kJ/mole), allowing rapid cycling of the sorbent.
- Low heat of adsorption and desorption:
  - The relatively low heats (28 kJ/mole) indicate that this process has a low heat demand for regeneration and low cooling requirements.
- High hydrothermal stability:
  - Direct heating with steam can be used for CO_2 desorption.

CO_2 Adsorption Isotherms



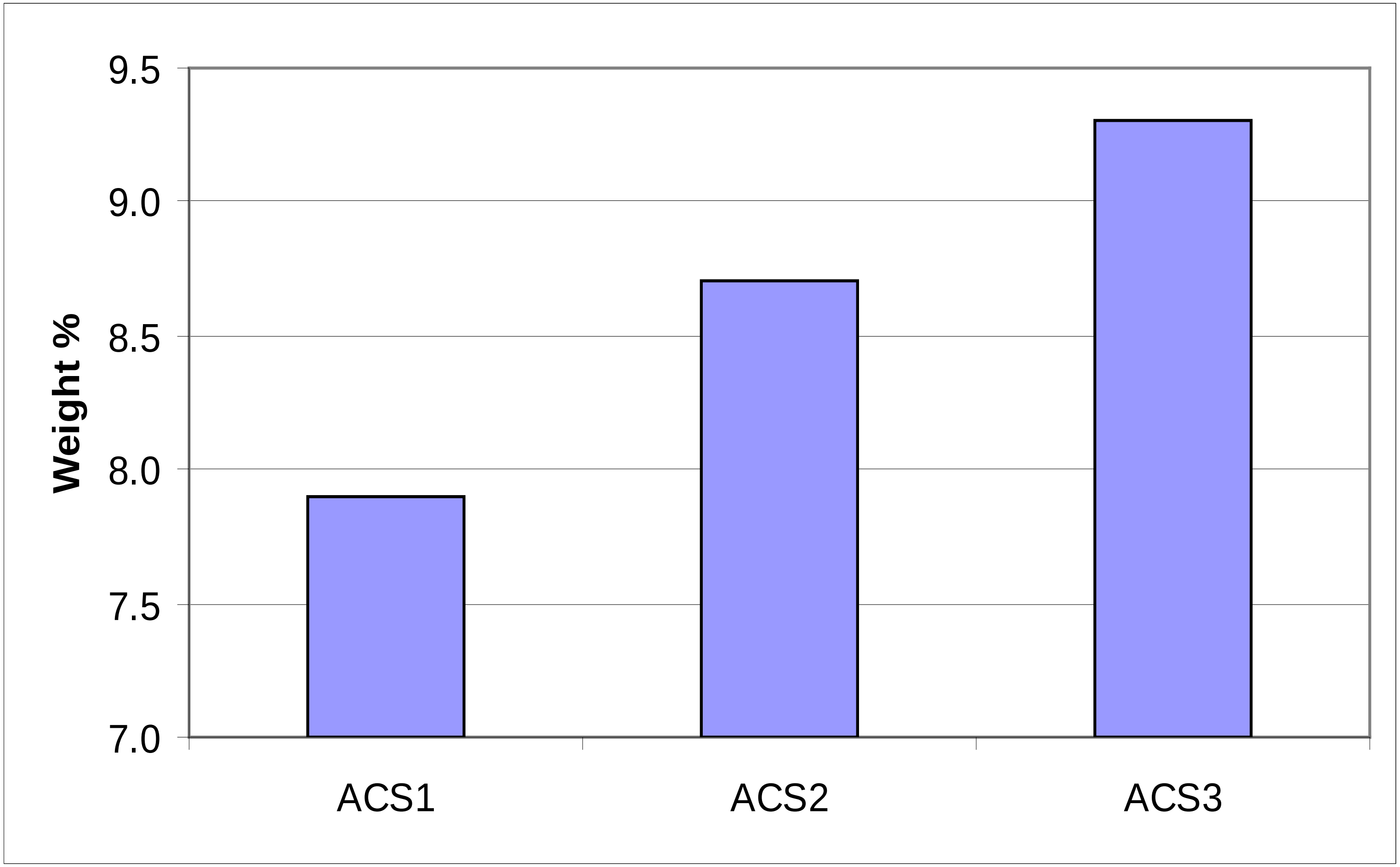
100 cm^3/g = 20 wt% CO_2

Heat of Adsorption for CO_2



Note: Measured heat of desorption = 27 kJ/mole

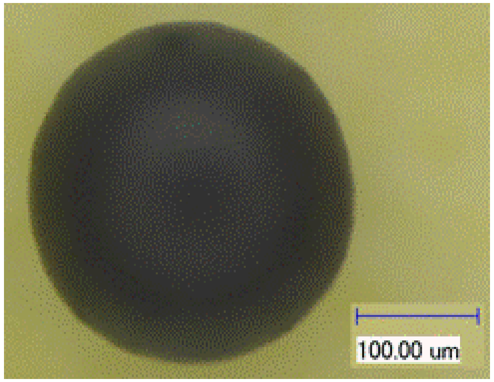
Differential CO_2 loading Between 30° and 110°C

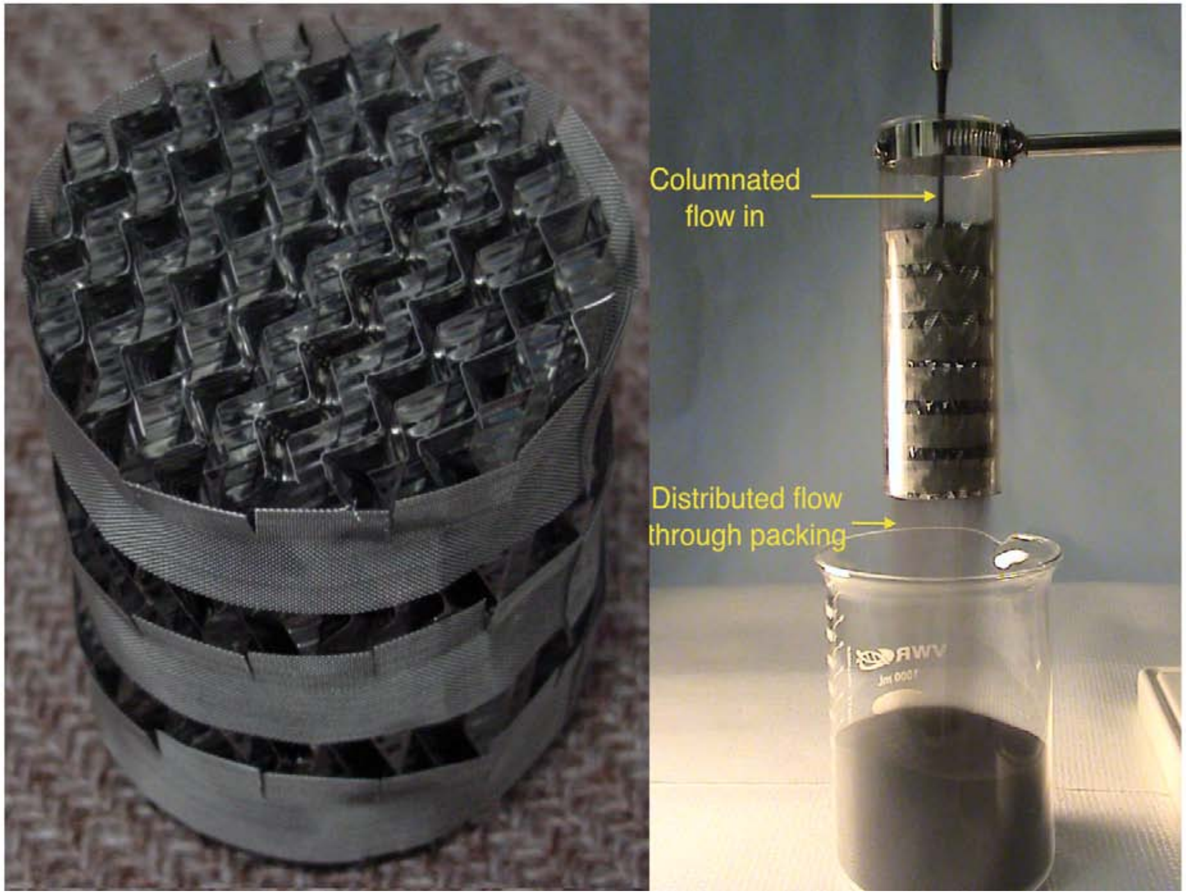


Merits of the Sorbent – Physical Properties

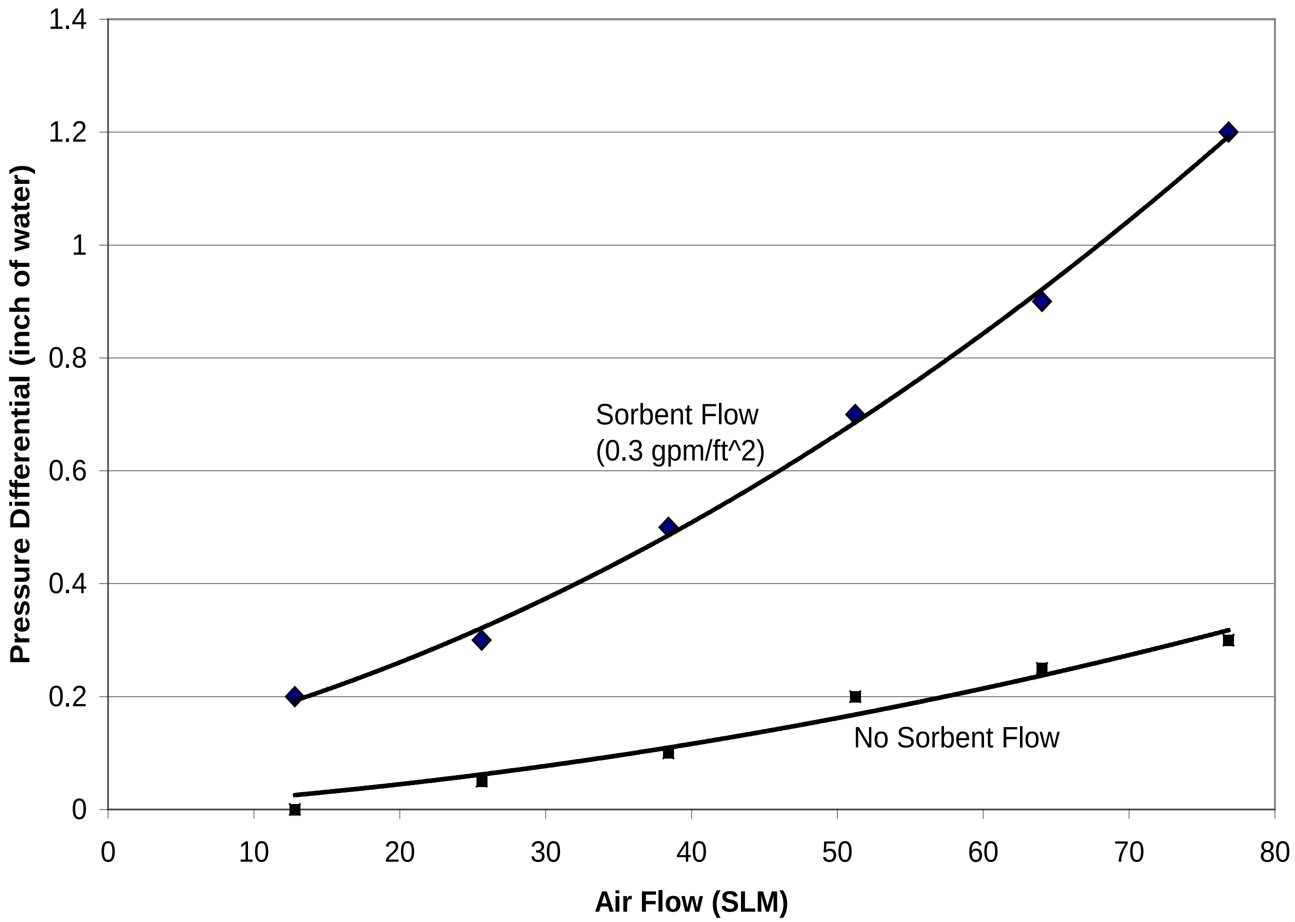
- Mechanical robustness for long lifetime:
  - Hard and attrition resistant; Unusually tough for a high surface area (1600 m^2/g) porous solid.
  - ASTM Test D-5757: Attrition resistance very high: Weight loss <0.01%/hour
- Spherical morphology of the sorbent granules:
  - The spherical nature of the sorbent granules (100 to 300 µm in diameter) allows a smooth flow on an inclined surface, like a ball bearing.
  - This free-flowing, liquid-like characteristic allows the use of commercially available structural packing as the gas-solid contacting device.
- Low heat capacity:
  - The low heat capacity of the sorbent (1 J/g/K) and low density (1 kg/m^3) minimizes the thermal energy needed to heat the sorbent to the regeneration temperature.
- High thermal conductivity:
  - The thermal conductivity of 0.8 w/m-K enables rapid thermal equilibrium between the surface and interior.

Fluid-like Flow of Sorbents Through a Commercial Structural Packing





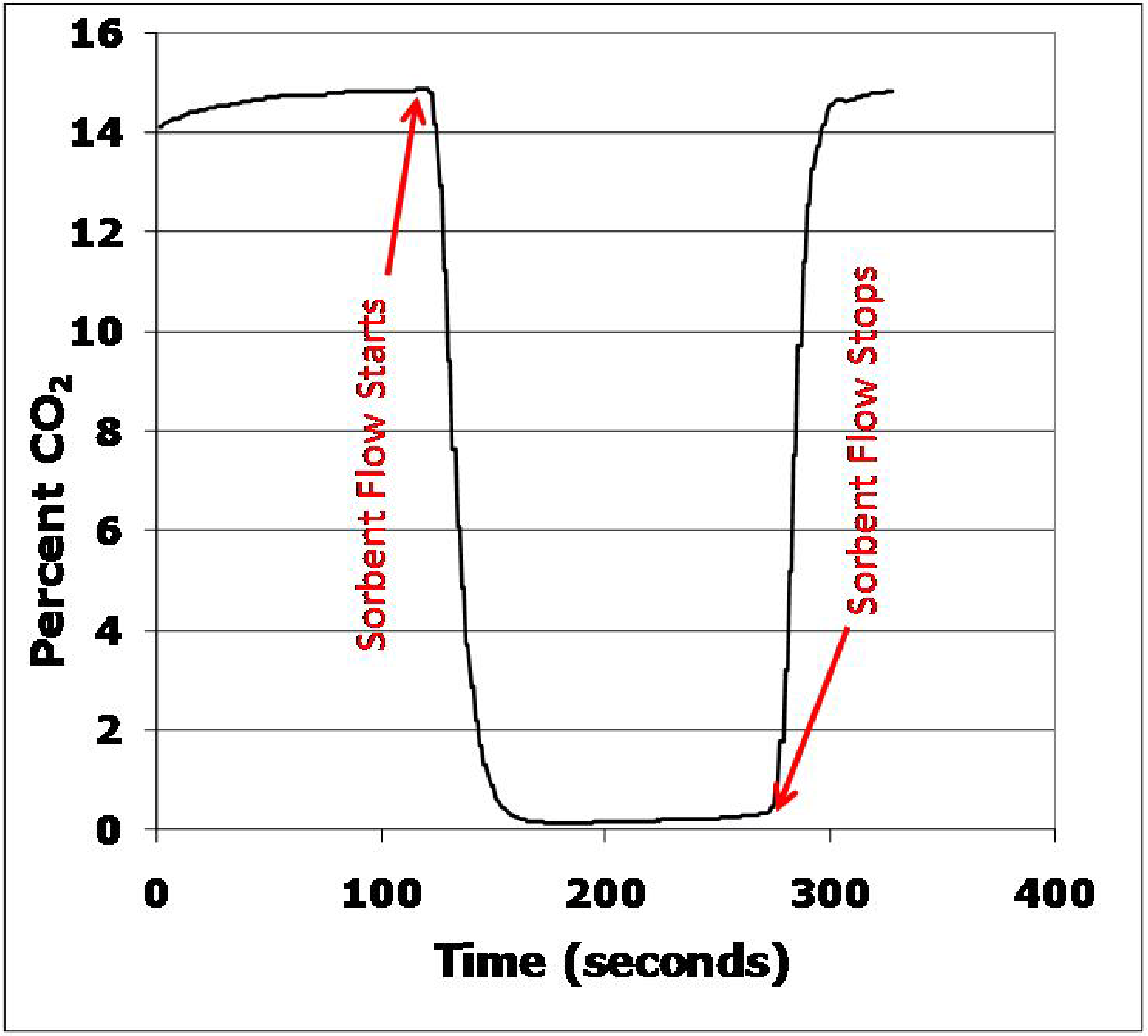
Pressure Drop in the Absorber



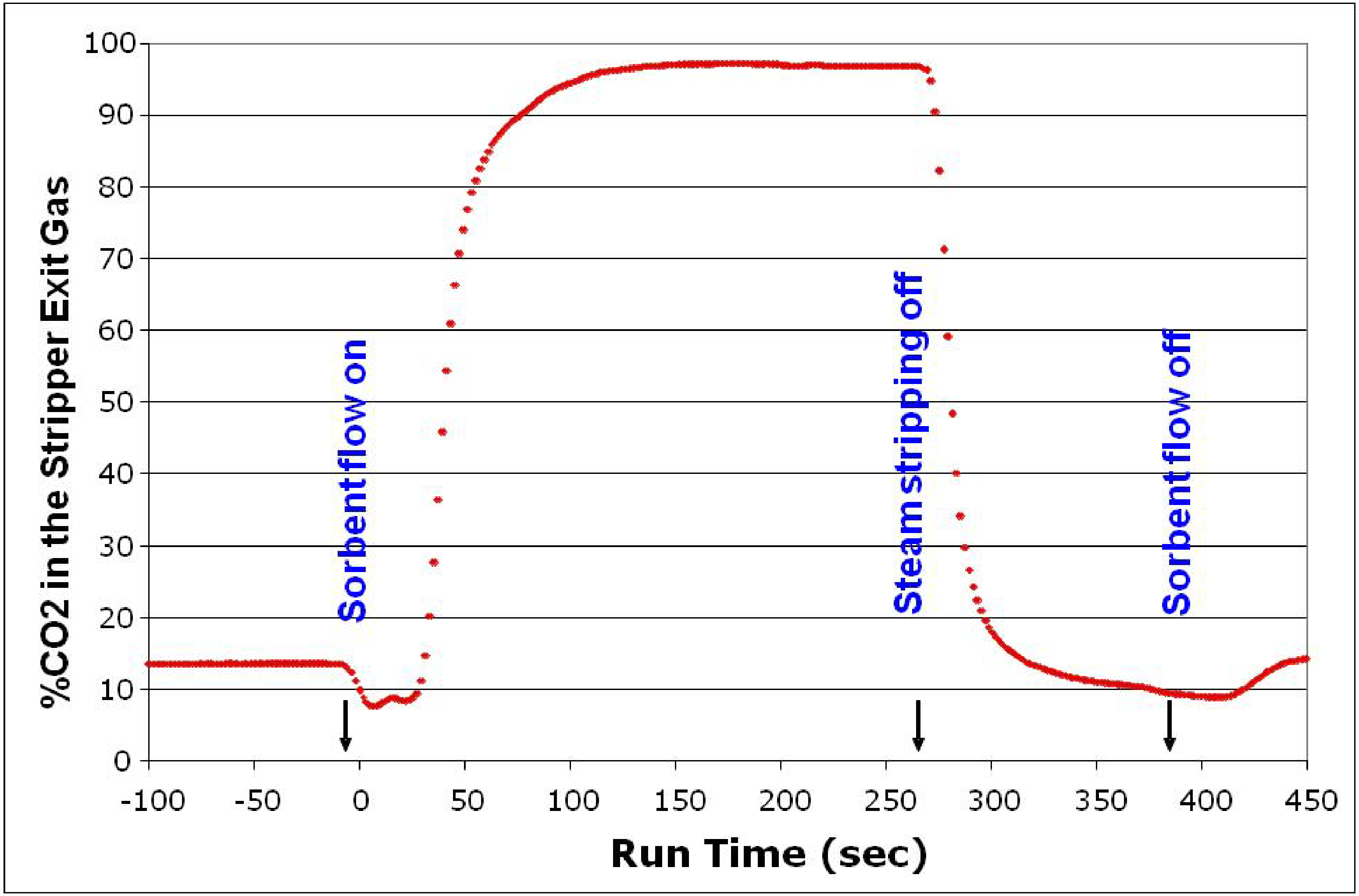
Flow rate of 100 Std.liters/min= 0.91 m/s

Rapid Adsorption and Desorption of CO_2

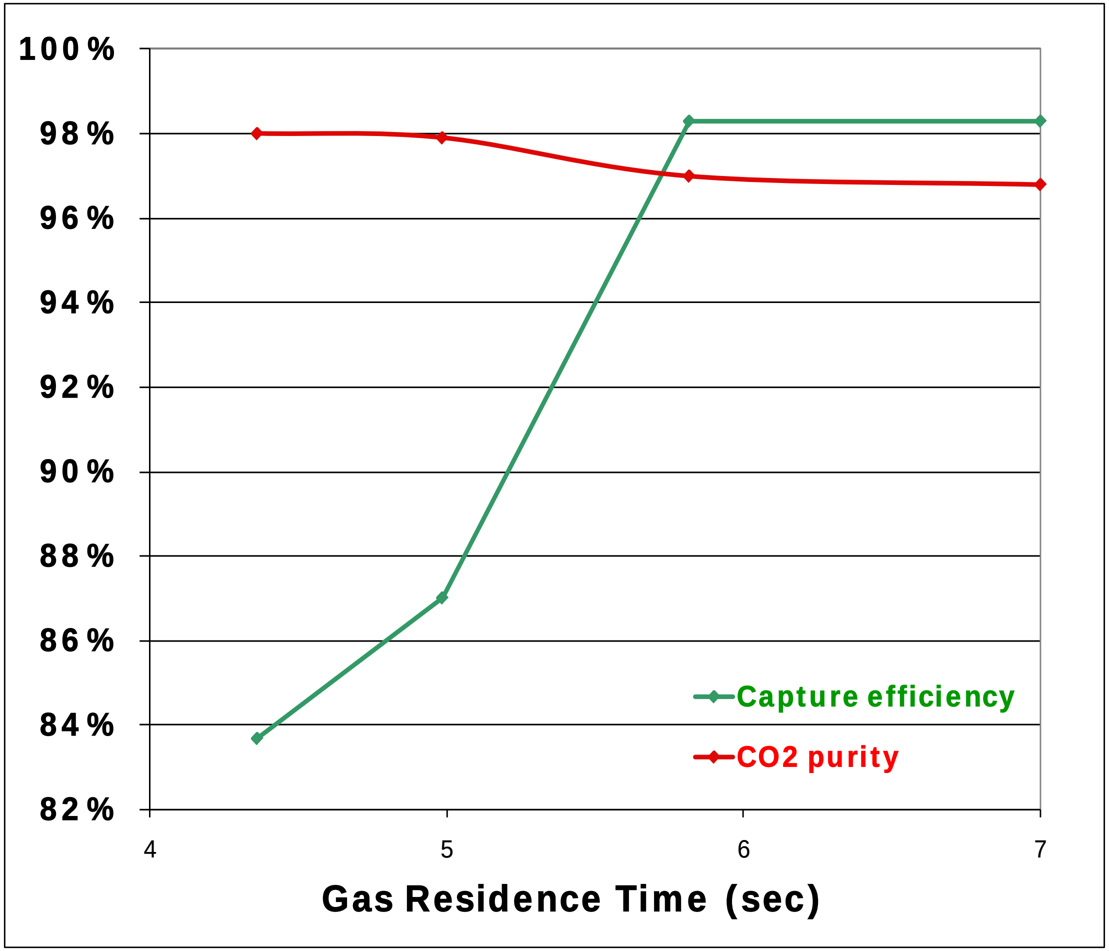
Removal of CO_2 from Air-CO_2 Mixture



Evolution of CO_2 in the Stripper

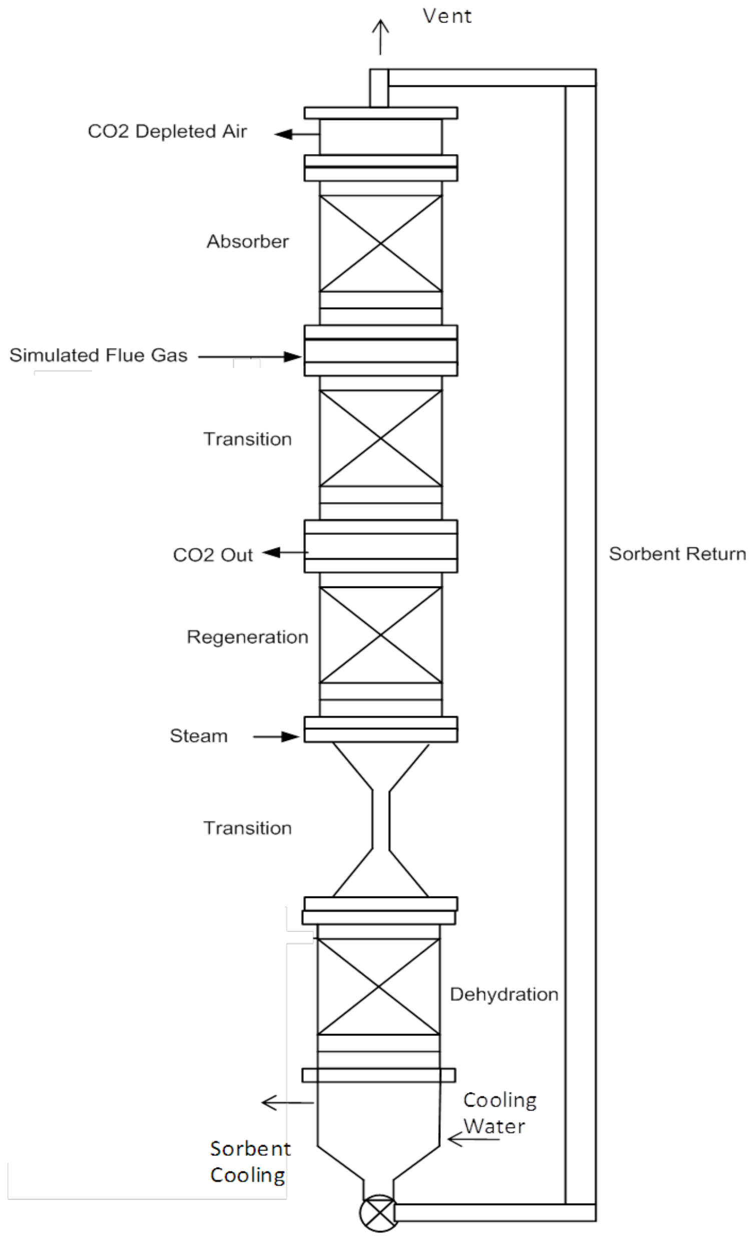


Capture Efficiency and Product Purity

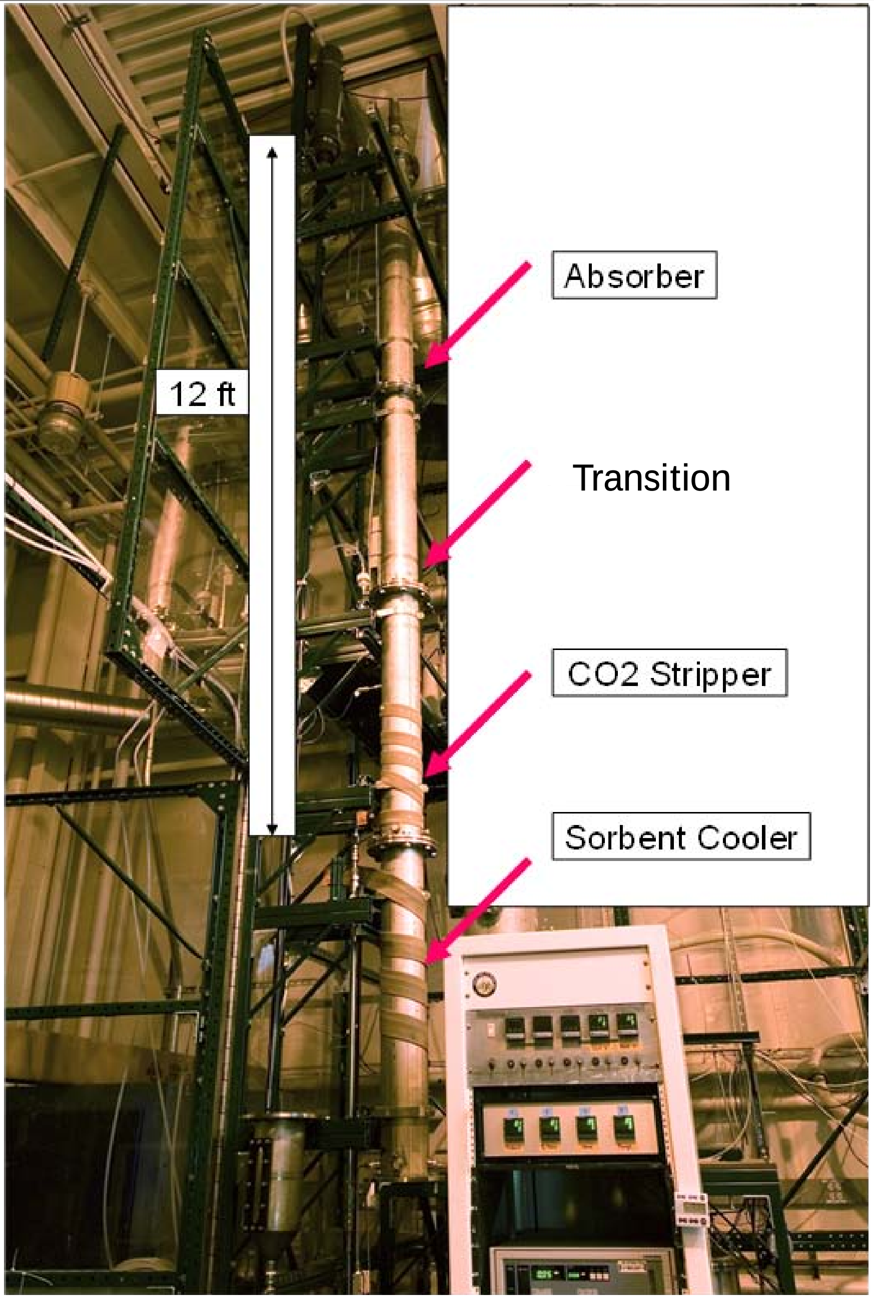


Integrated Absorber-Stripper System – Long Term Testing

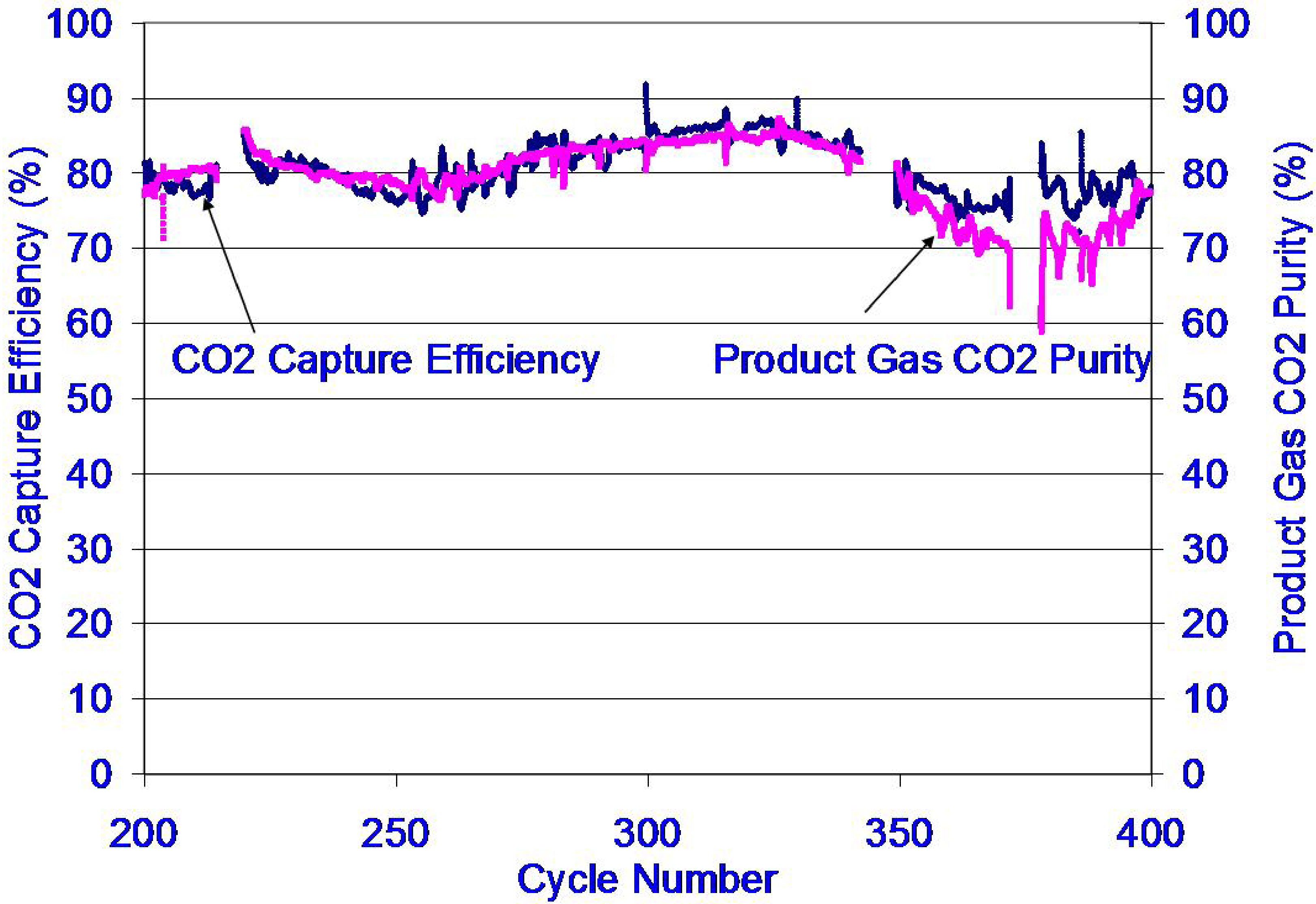
Schematic Diagram of Integrated System



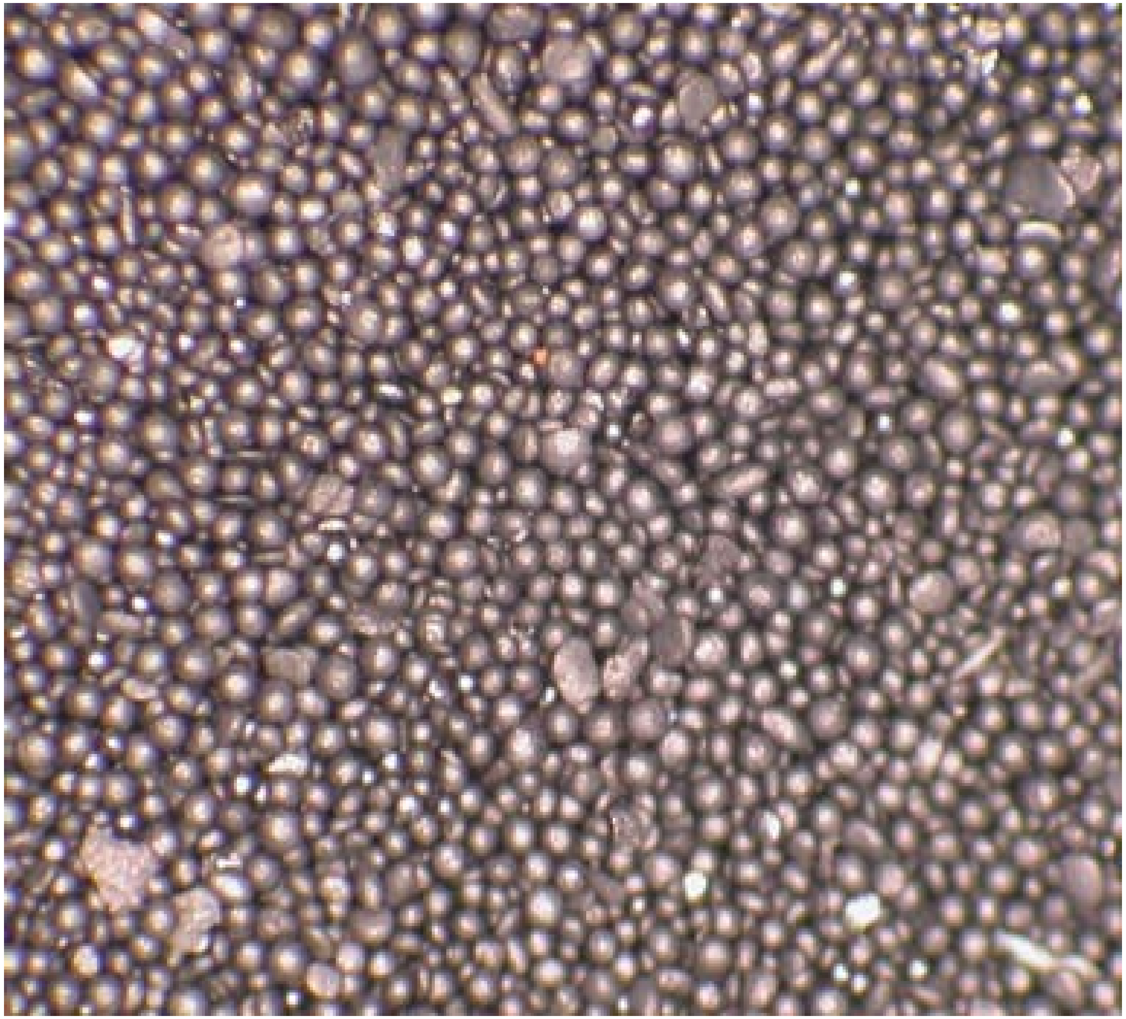
Photograph of Integrated System



Long-Term Testing (Earlier Data)

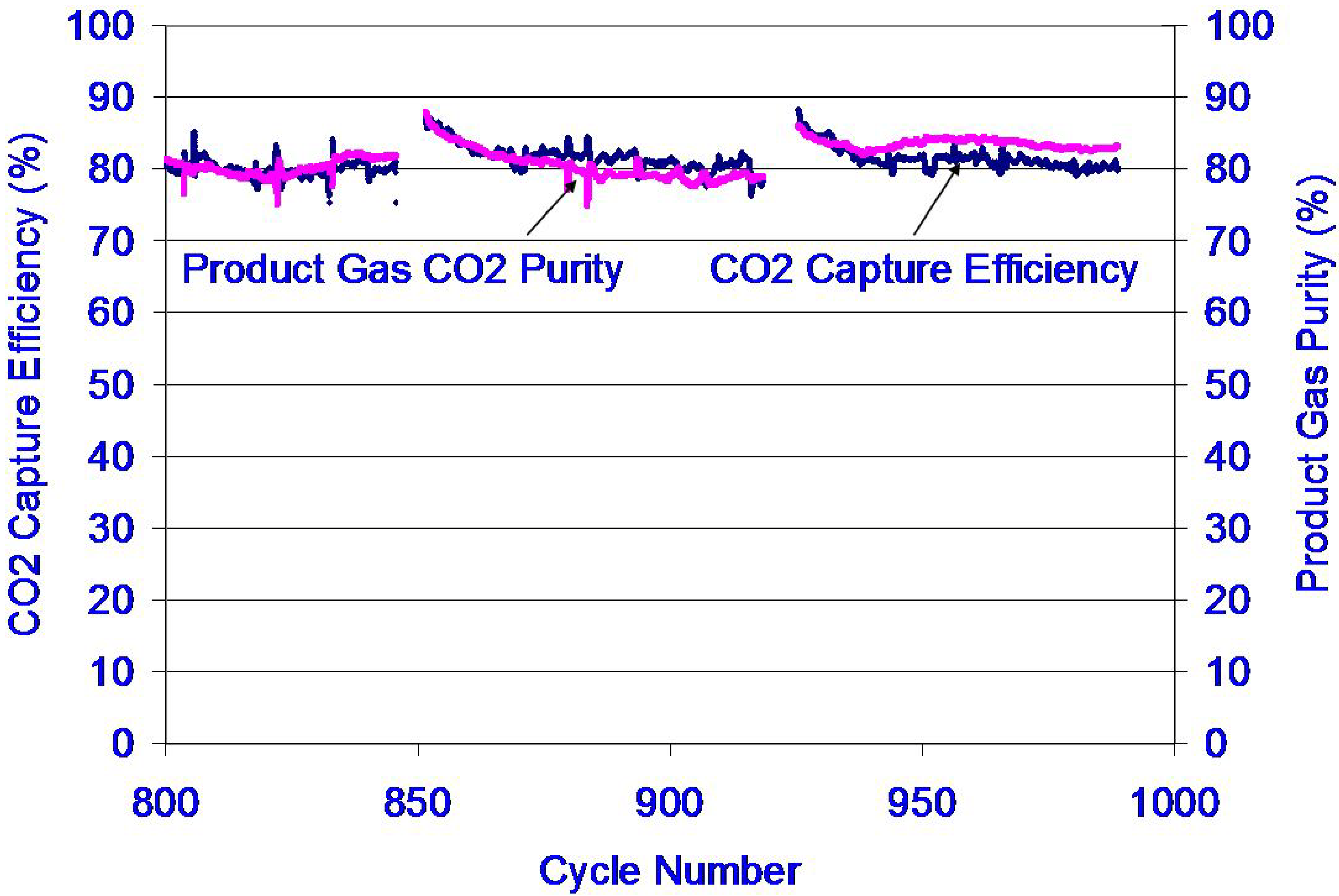


Fine Particles Recovered from Absorber Exhaust

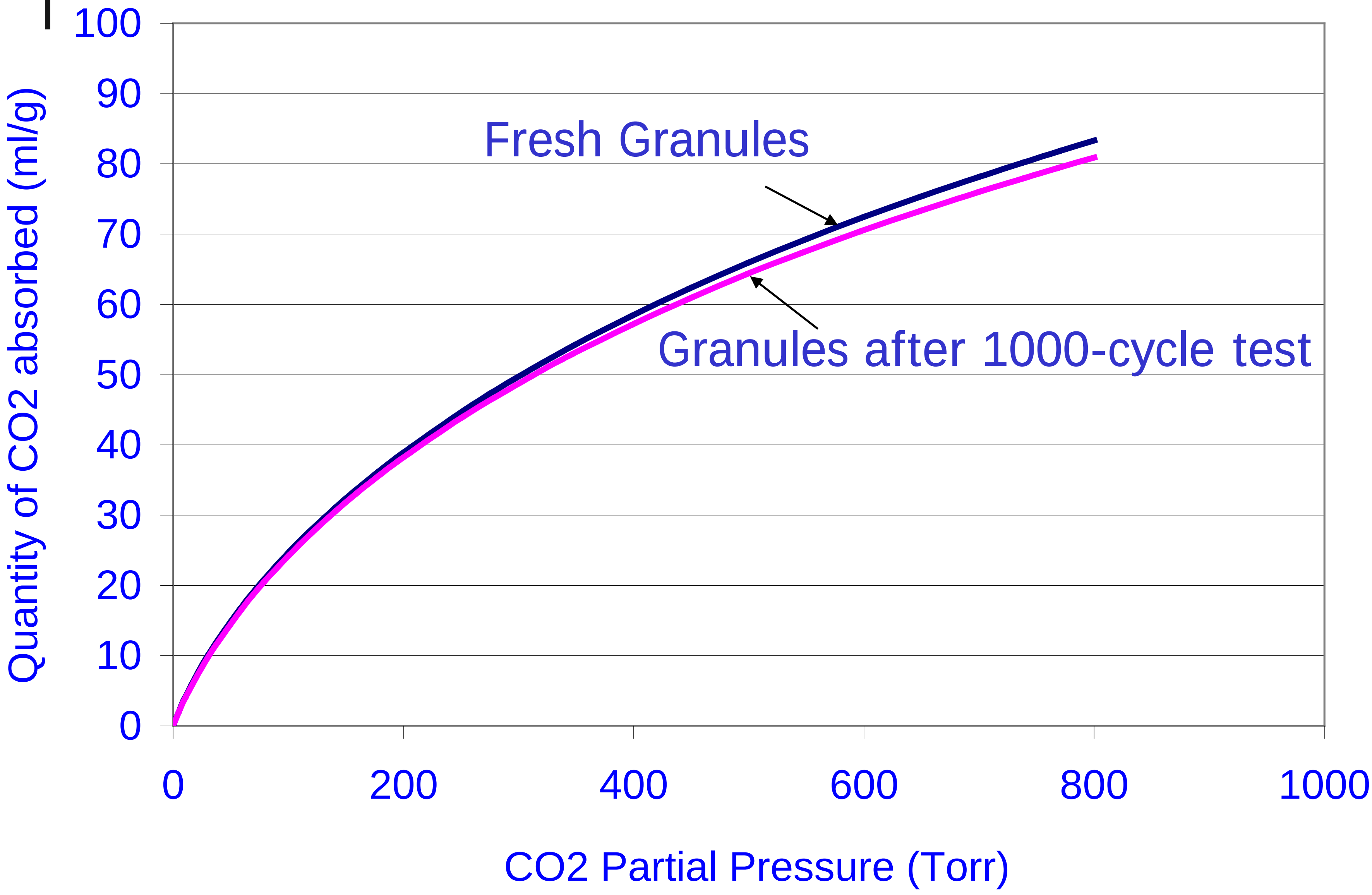


50-hour Test Duration.

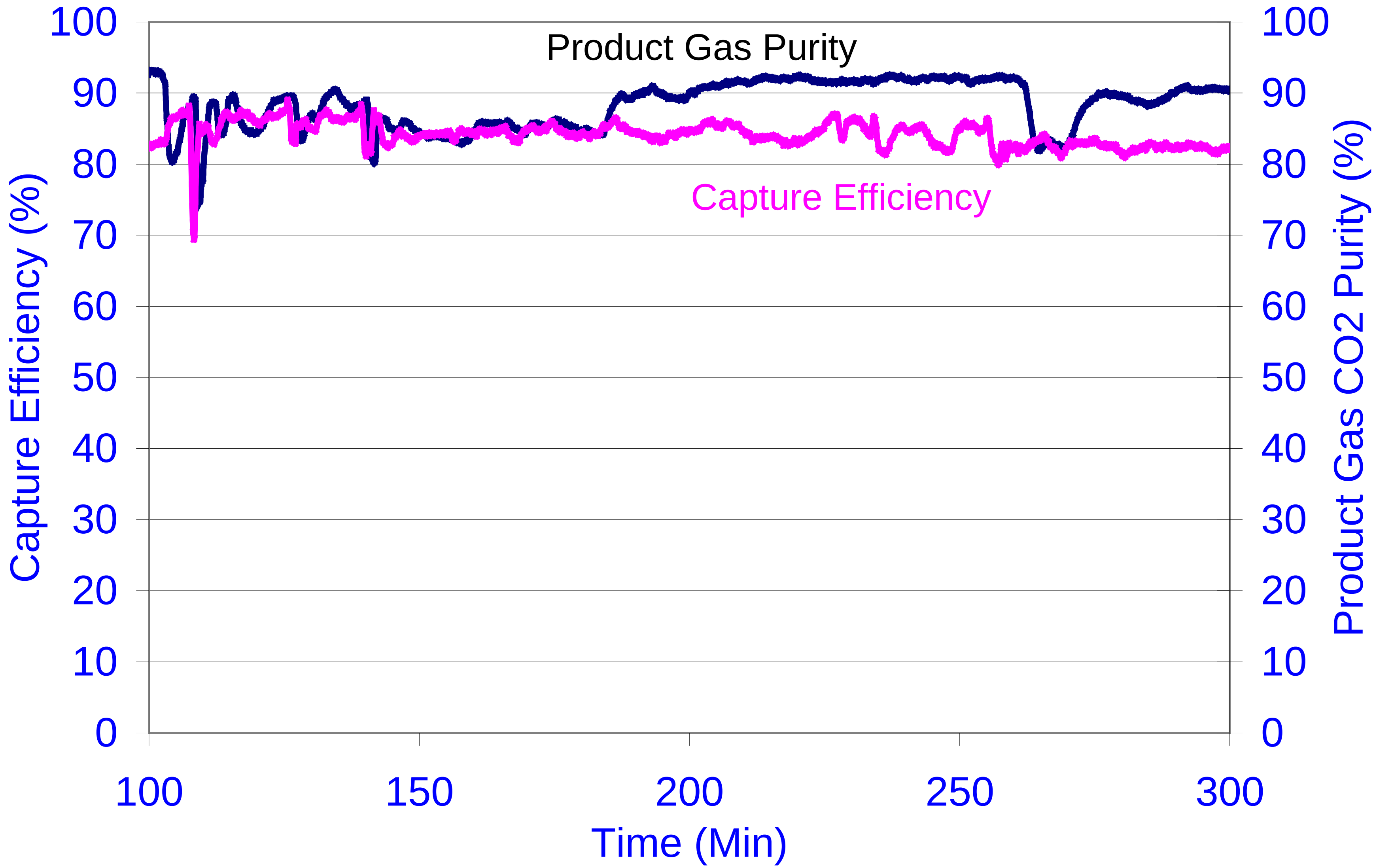
Long-Term Testing (Later Data)



Negligible Change in CO_2 Capacity



Improved Operation



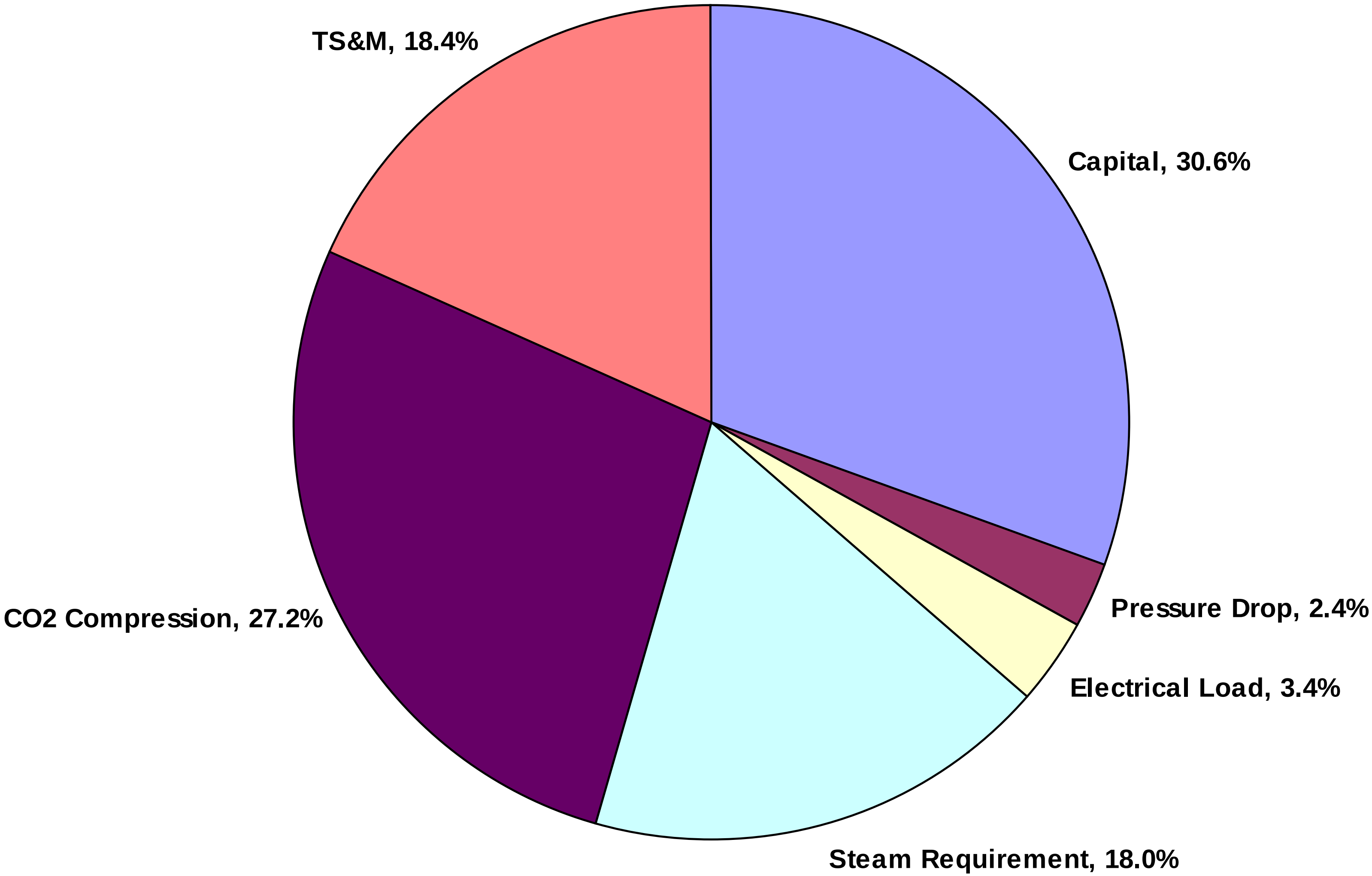
Technical and Economic Analysis

- Steam-Pro modeling was used to generate the equipment sizing and heat and material flows.
- Use DOE cost models.
- Base case is an air-fired greenfield supercritical PC plant (700 MWe nominal) with no CO_2 capture.
- Compare a similar-size plant using CO_2 capture with carbon sorbent subsystem.

Comparison of CO_2 Capture Costs

	Base Case	Econamine FG+	Carbon Sorbent
CO_2 Capture	**No**	**Yes**	**Yes**
Gross Power Output (kW)	581,034	679,911	640,421
Auxiliary Power Requirement (kW)	31,016	129,485	90,246
Net Power Output (kW)	**550,018**	**550,426**	**550,175**
Net Plant HHV Efficiency (%)	**38.9%**	**27.1%**	**35.1%**
Net Plant HHV Heat Rate (Btu/kW-hr)	8,859	12,590	9,717
Coal Flowrate (lb/hr)	414,000	594,000	458,280
CO_2 Emissions (lb/MWh)	1,790	252	194
Total Plant Cost ($ x 1000)	872,118	1,586,765	1,224,213
Total Plant Cost ($/kW)	1,586	2,883	2,225
LCOE (¢/kWh)	**6.40**	**11.58**	**9.23**
Increase in COE (%)	**0.0%**	**80.9%**	**44.2%**

Break-Down of the CO_2 Capture Cost Using Advanced Carbon Sorbent



Achievements

- Determined several physical and chemical properties of the advanced carbon sorbent in the context of flue gas CO_2 capture.
- Demonstrated an unique sorbent for CO_2 capture
  - Achieved ~99% CO_2 capture from air-CO_2 gas mixture
  - Achieved >98% pure CO_2 during regeneration
  - Capable of rapid adsorption and regeneration
  - Low heat requirements for regeneration
  - Fluid-like flow properties
  - High attrition resistance
- Developed an unique reactor system
  - Integrated absorber-desorber geometry
  - Minimize solids handling
  - Minimize heat exchanger requirements
  - Stable operation over 1000 cycles

Future Plans

- Field Testing:
  - Field test the process with the bench-scale reactor using a flue gas from an operating coal-fired boiler.
  - Complete the preliminary economic analysis.
  - Test the process at a pilot-scale level at a PC-fired boiler site.